

## MANUSCRIPT

# HELIUM EVOLUTION FROM THE TRANSFER OF HELIUM SATURATED PROPELLANT IN SPACE <sup>(1)</sup>

Bich N. Nguyen  
Boeing Reusable Space Systems

## ABSTRACT

Helium evolution from the transfer of helium saturated propellant in space is quantified to determine its impact from creating a two-phase mixture in the transfer line. The transfer line is approximately ½ inch in diameter and 2400 inches in length comprised of the Fluid Interconnect System (FICS), the Orbiter Propellant Transfer System (OPTS) and the International Space Station (ISS) Propulsion Module (ISSPM). The propellant transfer rate is approximately 2 to 3 gallons per minute, and the supply tank pressure is maintained at approximately 250 psig.

## INTRODUCTION

One of the technical challenges in the development of a propellant transfer capability in space for a propulsion system is the helium evolution from helium saturated propellant. The topic of gas evolution is not new; however, the effect it has on the propellant transfer in space is. Most of us can relate to the concept of gas evolution from the experience of opening a "COKE" can under pressure. There is a manifestation of bubble-like foam discharging out of the can. This bubble-like foam is the effect of carbon dioxide (CO<sub>2</sub>) coming out of solution in the form of gas bubbles. Likewise, the process of helium coming out of helium saturated propellant exhibits the same phenomenon; however, it is to a lesser extent due to the fact that the concentration of saturated gas in each scenario is significantly different, and the rate of gas evolution is different.

During propellant transfer, the propellant begins at the supply tank as a single-phase liquid. As it travels along the transfer line, it experiences pressure drop due to line friction, restrictions, and changes in

---

<sup>1</sup> This work was performed under NASA Contract No. NAS15-10000 to develop the International Space Station Propulsion Module (ISSPM).

flow direction. As a result of the pressure drop, the helium saturated propellant releases helium. Reference 1 states that: *"At a specific temperature and pressure, any liquid will hold a given quantity of gas in solution. Increasing the gas pressure will increase the quantity of gas that can be held by the liquid. Under any set of conditions of pressure and temperature, a liquid that holds the maximum quantity of gas in solution is said to be saturated. If the pressure is reduced while all other conditions remain the same, the quantity of gas that can be held in solution is reduced and the liquid then contains more gas than it can hold in solution at the new lower pressure and is over saturated. The excess dissolved gas will come out of solution; and if the pressure is reduced sufficiently, the excess gas may be observed as small bubbles."*

When helium evolves from the propellant, it begins as tiny bubbles from the nucleation sites (surfaces) and also within the liquid. Once these tiny bubbles are formed, they will progressively grow as a function of pressure drop. As the bubbles grow in size, they mix with the propellant liquid to create a two-phase flow. The process of helium evolution in the transfer line is shown in Figure 1. Figure 1 illustrates a visual observation of de-saturating helium saturated water from approximately 250 psig to 0 psig through a 1-inch smooth transparent tubing.

The existence of two-phase flow will induce uncertainty in the flow meter reading, which is utilized to gage the amount of transferred propellant for a single-phase flow. To eliminate the effect of helium evolution on the flow meter uncertainty, the volume fraction of the helium to propellant is quantified so that undesirable region of two-phase flow can be avoided. Furthermore, upon completion of propellant transfer, the transfer line must be emptied of propellant prior to being disconnected. This requires that the transfer line be purged. Purging in micro-gravity condition is already difficult with the existence of valves and bends, and is now further complicated with the trapped helium bubbles. Under micro-gravity conditions, there is a tendency for the bubbles to merge and form a continuous gas passage. Reference 2 discusses the fluid behavior in micro-gravity condition. The purge gas will tend to travel along the lesser resistance path, which is the gas passage. Consequently, the effectiveness of the purging the residual propellant becomes questionable. Again, quantifying the volume fraction of the helium to propellant along the transfer line is necessary so that the impact of the trapped bubbles on purging can be assessed.

In this paper, the volume fraction of helium to propellant in the transfer line is determined based on the line configurations of the FICS, OPTS, and ISSPM. The Orbiter docking with the ISS during the propellant transfer is shown in Figure 2.

## SYMBOLS

Values are given in U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

MMH	Monomethylhydrazine, fuel
NTO	Nitrogen tetroxide, oxidizer
x	Distance from the supply tank along the transfer line, inch
Q	Volumetric flow rate, gpm
D	Inner diameter of the transfer line, inch
V	Volume of the propellant element, in <sup>3</sup>
v	Velocity of the fluid flowing inside the transfer line, ft/sec
$\rho$	Density of the propellant, lbm/ft <sup>3</sup>
f	Friction factor, dimensionless
P	Local pressure inside the transfer line, psig
$\Delta P$	Pressure drop, psi
He <sub>MMH</sub>	Amount of helium absorbs in a given amount (cc) of MMH, cc at STP
He <sub>NTO</sub>	Amount of helium absorbs in a given amount (cc) of NTO, cc at STP
Q <sub>MMH</sub>	Total amount of helium absorbs in helium saturated MMH, cc at STP
Q <sub>NTO</sub>	Total amount of helium absorbs in helium saturated NTO, cc at STP
%He <sub>MMH</sub>	Percentage of helium evolves from helium saturated MMH at a 250 psig to a given de-saturation pressure, %
%He <sub>NTO</sub>	Percentage of helium evolves from helium saturated NTO at a 250 psig to a given de-saturation pressure, %
G <sub>MMH</sub>	Total amount of helium evolves from MMH during MMH transfer, cc at STP
G <sub>NTO</sub>	Total amount of helium evolves from NTO during NTO transfer, cc at STP
R <sub>MMH</sub>	The volume fraction of helium to propellant evolves from MMH during MMH transfer, dimensionless
R <sub>MMH</sub>	The volume fraction of helium to propellant evolves from MMH during MMH transfer, dimensionless

## ANALYTICAL APPROACH

The helium evolution upon de-saturation of a helium-saturated propellant is a kinetic process. That is, the evolution of helium occurs instantaneously with respect to decreasing pressure. It is a technical challenge to design a test apparatus to measure the transient helium evolution. Furthermore, there is a lack of test data on the kinetic helium evolution to correlate the direct effect of helium evolution with time under the proposed propellant transfer conditions. As an alternative, a steady-state condition for helium evolution was utilized to arrive at (1) the total amount of helium evolution and (2) the steady-state time. These results are sufficient to address the concerns of helium evolution on the flow meter and on the effectiveness of purging. Consequently, the need for the actual kinetic helium evolution is not necessary.

The pressure drop forces the helium gas to evolve from helium saturated propellant. The higher the pressure drop the more helium evolution. Thus, the characterization of helium evolution requires a complete understanding of the pressure drop characteristics of the transfer system.

## PRESSURE DROP CHARACTERIZATION

### Configuration

The FICS and OPTS are shown in Figure 3. The propellant can be transferred either from the Forward Reaction Control System (FRCS), the Orbiter Maneuver System (OMS), or the Aft Reaction Control System (ARCS). The FRCS is located near the lower left-hand side, and the OMS and ARCS are located near the lower right-hand side of Figure 3. As the propellant leaves the supply tanks, it enters the FICS and subsequently flows into the OPTS which leads to the ISSPM. The OPTS is located near the upper left-hand side of Figure 3.

### Pressure Drop Formulation

The pressure at any point in the transfer line is equal to the supply tank pressure minus the accumulated pressure drop from the supply tank to that point. Since the ISSPM is a bi-propellant propulsion system, which utilizes Monomethylhydrazine ( $\text{MMH-CH}_3\text{N}_2\text{H}_2$ ) as a fuel and Nitrogen Tetroxide ( $\text{NTO-N}_2\text{O}_4$ ) as an oxidizer, the following analyses will provide derivations for both commodities. The line pressure drop is:

$$P_i = 250 - \Delta P_{line} - \Delta P_{bend} - \Delta P_{valve} \quad (1)$$

where

$$\Delta P_{line} = \frac{1}{2} \left( \frac{1}{144 * 32.2} \right) \frac{\rho_i}{D} v^2 f_i x \quad (1-1)$$

$$\Delta P_{bend} = \sum_{m=1}^M \frac{1}{2} \left( \frac{1}{144 * 32.2} \right) \rho_i v^2 K(\text{angle}_m, f_i) \quad (1-2)$$

$$\Delta P_{valve} = \sum_{n=1}^N \frac{1}{2} \left( \frac{1}{144 * 32.2} \right) \rho_i v^2 K_n f_i \quad (1-3)$$

i represents the commodity: MMH or NTO

The physical properties of MMH and NTO were obtained from Reference 3.

The pressure drop is a function of flow rate, which is dependent on the pressure difference between the supply tank and the receiving tank. The supply tank pressure is regulated to approximately 250 psig; however, the receiving tank pressure increases with the transferred propellant. This causes the pressure difference between tanks to decrease. Consequently, the flow rate decreases accordingly. In this report, the pressure drop analysis is assumed that the flow rate is controlled to maintain a constant flow. The pressure profile during propellant transfer is shown in Figure 4. Figure 4 shows that the pressure drop increases abruptly in transition from one subsystem to the next due to multiple redundancy isolation valves.

## HELIUM ABSORPTION and EVOLUTION CHARACTERIZATION

Before beginning the analysis of helium evolution during propellant transfer, it is important to define the amount of helium absorption and evolution in MMH and NTO

### Helium Absorption

When propellant is pressurized with helium gas, the helium will be absorbed in the propellant. Reference 1 shows that the amount of helium saturated at Standard Temperature and Pressure (STP) in MMH and NTO can be described by the following correlation.

$$He_{MMH}(P) = 0.0006P - 0.00323 \quad (2)$$

$$He_{NTO}(P) = 0.0022P - 0.0863 \quad (3)$$

The amount of helium absorption in the propellant increases with increasing pressure. NTO can absorb 3 to 4 times more helium at a given pressure than that for MMH.

### Helium Evolution

Helium evolves when the pressure of helium saturated propellant is de-saturated. The lower the de-saturation pressure the larger the amount of helium will evolve. Reference 1 shows that the percentage of helium evolution upon de-saturation can be described by the following correlation.

$$\%He_{MMH}(P) = -0.518P + 128.87 \quad (4)$$

$$\%He_{NTO}(P) = -0.474P - 118.47 \quad (5)$$

The percentage of helium evolution increases with decreasing pressure. The percentage of helium evolution is similar for both MMH and NTO even though the absorption capability varies by 3 to 4 times. The propellants were initially saturated with helium at 250 psig.

### Helium Evolution upon Propellant Transfer

Now that the helium absorption and evolution in MMH and NTO are defined, the analysis of the helium evolution inside the transfer line during propellant transfer is ready to proceed. Consider an element of propellant at a distance  $x$  from the supply tank as shown in Figure 7.

The local line pressure,  $P$ , is defined by Equation 1. This propellant element is initially saturated with a given amount helium as defined by Equations 2 and 3. As it leaves the supply tank, it experiences pressure drop, which causes it to release the excess helium. The percentage of helium evolution is defined by Equations 4 and 5. The amount of helium that comes out of solution can now be calculated based on the Equations 2 through 5. For a given de-saturation pressure, the amount of helium coming out of solution is:

$$G_{commodity} = Q_{commodity}(P) [\%He_{commodity}(P)] \quad (6)$$

Equation 6 states that, for a given elemental volume  $dV$ , the amount of helium that evolves from the propellant is a percentage of the total amount of helium saturated within that elemental volume at a given pressure.

Differentiating Equation 6 yields

$$dQ_{commodity} = dQ_{commodity}(P) \left[ \%He_{commodity}(P) \right] + Q_{commodity}(P) \frac{d[\%He_{commodity}(P)]}{dP} \frac{dP}{dx} dx \quad (7)$$

For a given volume of propellant, the total amount of helium saturated can be determined as follows:

$$Q_{commodity} = VHe_{commodity}(P)$$

$$dQ_{commodity} = He_{commodity}(P)dV + V \frac{dHe_{commodity}(P)}{dP} \frac{dP}{dx} dx$$

$$Q_{commodity} = \left( \frac{1}{0.0610} \right) \left( \frac{\pi D^2}{4} \right) \int_0^x \left[ He_{commodity}(P) + \frac{dHe_{commodity}(P)}{dP} \frac{dP}{dx} x \right] dx$$

Hence, the total amount of helium evolves from an elemental volume of propellant during propellant transfer is

$$\text{For MMH, } dG_{MMH} = dQ_{MMH}(x) [\%He_{MMH}(P)] + Q_{MMH}(x) \frac{d[\%He_{MMH}(P)]}{dP} \frac{dP}{dx} dx \quad (7-1)$$

$$dG_{MMH} = \left( \frac{1}{0.0610} \right) \left( \frac{\pi D^2}{400} \right) \left( -0.518P + 128.87 \right) \left[ (0.0006P - 0.0323) + 0.0006x \frac{dP}{dx} \right] dx + \left( \frac{1}{0.0610} \right) \left( \frac{\pi D^2}{400} \right) \left( -0.518 \frac{dP}{dx} \right) \left[ \int_0^x (0.0006P - 0.0323) + 0.0006x \frac{dP}{dx} dx \right] dx$$

$$\text{For NTO, } dG_{NTO} = dQ_{NTO}(P) [\%He_{NTO}(P)] + Q_{NTO}(P) \frac{d[\%He_{NTO}(P)]}{dP} \frac{dP}{dx} dx \quad (7-2)$$

$$dG_{NTO} = \left( \frac{1}{0.0610} \right) \left( \frac{\pi D^2}{400} \right) \left( -0.474P + 118.47 \right) \left[ (0.0022P - 0.0863) + 0.0022x \frac{dP}{dx} \right] dx + \left( \frac{1}{0.0610} \right) \left( \frac{\pi D^2}{400} \right) \left( -0.474 \frac{dP}{dx} \right) \left[ \int_0^x (0.0022P - 0.0863) + 0.0022x \frac{dP}{dx} dx \right] dx$$

The total amount of helium evolution inside the propellant transfer line can now be calculated by integrating Equations 7-1 and 7-2 from  $x=0$  to  $x$

$$G(x) = \int_0^x \frac{dG}{dx} dx \quad (8)$$

$$\text{For MMH, } G_{MMH}(x) = \int_0^x \frac{dG_{MMH}}{dx} dx \quad (8-1)$$

$$G_{MMH}(x) = \left( \frac{1}{0.0610} \right) \left( \frac{\pi D^2}{400} \right) \int_0^x \left( -0.518P + 128.87 \right) \left[ (0.0006P - 0.0323) + 0.0006x \frac{dP}{dx} \right] dx + \left( \frac{1}{0.0610} \right) \left( \frac{\pi D^2}{400} \right) \int_0^x \left( -0.518 \frac{dP}{dx} \right) \left[ \int_0^x \left[ (0.0006P - 0.0323) + 0.0006x \frac{dP}{dx} \right] dx \right] dx$$

Figure 6 shows that the helium evolution from MMH increases with increasing flow rate. The pressure drop increases with increasing flow rate. Thus, the higher the flow rate the higher the helium evolution. However, it should be noticed that these results are based on STP conditions. The maximum amount of helium evolution at 3.0 gpm is approximately 100 cc at STP. The total amount of helium saturated in MMH at 250 psig inside the transfer line is approximately 1134 cc at STP. Thus, the percentage of helium evolves inside the transfer line is approximately 8.8%.

Similarly,

$$\text{For NTO, } G_{NTO} = \int_0^x \frac{dG_{NTO}}{dx} dx \quad (8-3)$$

$$G_{NTO} = \left( \frac{1}{0.0610} \right) \left( \frac{\pi D^2}{400} \right) \int_0^x \left( -0.474P + 118.47 \right) \left[ (0.0022P - 0.0863) + 0.0022x \frac{dP}{dx} \right] dx + \left( \frac{1}{0.0610} \right) \left( \frac{\pi D^2}{400} \right) \int_0^x \left( -0.474 \frac{dP}{dx} \right) \left[ \int_0^x \left[ (0.0022P - 0.0863) + 0.0022x \frac{dP}{dx} \right] dx \right] dx$$

Similarly, Figure 7 shows that the helium evolution increases with increasing transfer rate. However, the amount of helium evolution from NTO is approximately 3 to 4 times larger than that for MMH. This result is consistent with the absorption ratio between NTO and MMH. The maximum amount of helium evolution at 3.0 gpm is approximately 550 cc at STP. The total amount of helium saturated in NTO at 250 psig inside the transfer line is approximately 3582 cc at STP. Thus, the percentage of helium evolves inside the transfer line is approximately 15.3%. Since the



calculation was based on STP conditions, the volumetric amount of helium evolution will be much smaller at the actual line pressure.

### Volume Fraction of Helium to Propellant upon Propellant Transfer

It is pertinent at this time to correlate the volume fraction of the helium evolution at the local line pressure condition so that a better perspective of the relative size of helium bubbles can be examined.

The volume fraction of helium to propellant is defined as the ratio of the volume of the helium evolution at line pressure to that of the line (or propellant) volume from the supply tank to x.

$$\text{For MMH, } R_{MMH}(x) = (0.0610) \left( \frac{1}{V} \right) \left( \frac{14.7}{14.7 + P} \right) G_{MMH}(x) \quad (8-2)$$

$$R_{MMH}(x) = \left( \frac{1}{100} \right) \left( \frac{14.7}{14.7 + P} \right) \left( \frac{1}{x} \right) \int_0^x \left( -0.518P + 128.87 \right) \left[ (0.0006P - 0.0323) + 0.0006x \frac{dP}{dx} \right] dx + \\ \left( \frac{1}{100} \right) \left( \frac{14.7}{14.7 + P} \right) \left( \frac{1}{x} \right) \int_0^x \left( -0.518 \frac{dP}{dx} \right) \left\{ \int_0^x \left[ (0.0006P - 0.0323) + 0.0006x \frac{dP}{dx} \right] dx \right\} dx$$

Figure 8 shows the volume fraction of helium to MMH in the transfer line. The volume fraction of the helium gas evolution is approximately 0.1% of the line volume at 3 gpm. That is, for every cubic inch of the transfer line, there is a 1/1000 cubic inch of the helium gas. The total transfer line volume is approximately 7725 cc. The total volume of the helium gas evolution at line pressure is approximately 7.7 cc. This is equivalent to approximately 0.5 cubic inch.

$$R_{NTO}(x) = (0.0610) \left( \frac{1}{V} \right) \left( \frac{14.7}{14.7 + P} \right) G_{NTO}(x) \quad (8-4)$$

$$R_{NTO} = \left( \frac{1}{100} \right) \left( \frac{14.7}{14.7 + P} \right) \left( \frac{1}{x} \right) \int_0^x \left( -0.474P + 118.47 \right) \left[ (0.0022P - 0.0863) + 0.0022x \frac{dP}{dx} \right] dx + \\ \left( \frac{1}{100} \right) \left( \frac{14.7}{14.7 + P} \right) \left( \frac{1}{x} \right) \int_0^x \left( -0.474 \frac{dP}{dx} \right) \left\{ \int_0^x \left[ (0.0022P - 0.0863) + 0.0022x \frac{dP}{dx} \right] dx \right\} dx$$

Figure 9 shows the volume fraction of helium to NTO in the transfer line. The volume fraction of helium is approximately 0.6% of the

line volume at 3 gpm. That is, for every cubic inch of the transfer line, there is a 6/1000 cubic inch of the helium gas. For a line volume of 7725 cc, the total volume of the helium gas evolution at line pressure is approximately 46.4 cc. This is equivalent to approximately 2.8 cubic inch.

### Steady-State Timeline of Helium Absorption and Evolution

As mentioned earlier, helium evolution is a kinetic process. However, the concern about helium evolution during propellant transfer does not require a full understanding of the kinetic process. Furthermore, there is a lack of test data on the kinetic of helium evolution to address this concern. Therefore, the following approach was applied, which was driven by the availability of data on (1) steady-state helium absorption and evolution and (2) the steady-state timeline of helium absorption and evolution.

Boeing Reusable Space Systems <sup>(2)</sup> has conducted some preliminary de-saturation tests with helium saturated MMH and NTO to determine the timeline of helium absorption and evolution. The test was conducted utilizing a Hoke bottle, which was filled with MMH or NTO. The MMH or NTO was subsequently pressurized with helium gas over an extended period of time to obtain a helium saturated propellant condition. The saturated condition was verified by either bubble point pressure or by an indication of ullage pressure drops. Reference 4 discusses the methodology of bubble point pressure. The pressure drop occurs when the helium is absorbed into the solution that causes the ullage pressure to decrease. Once the saturated condition was established, the ullage gas was vented to approximately ambient pressure and the Hoke bottle was completely closed. With the new lower pressure, the helium in the solution was over-saturated and came out of solution to re-establish a new helium-saturated condition. The steady-state timeline of helium absorption and evolution is shown in Table 1.

Although the test de-saturation pressure is much lower than the anticipated de-saturation pressure during propellant transfer, the result suggested that the rate of helium evolution be much faster than the rate of absorption.

---

<sup>2</sup> Boeing Reusable Space Systems, 5301 Bolsa Ave., Huntington Beach, CA 92647-2099.

## CONCLUSION

For a 2400-inch propellant transfer line, the volumes of helium evolution from helium saturated MMH and NTO are approximately 0.5 in<sup>3</sup> and 2.8 in<sup>3</sup>, respectively. These helium volumes are distributed over the length of 2400 inches. Consequently, the impact of helium evolution on flow meter and on the ability to purge is insignificant. However, it is recommended that the flow meter be placed as close to the supply tank as practical.

The steady-state time evolution is significantly faster than that of the absorption. The steady-state evolution times for MMH and NTO are approximately 1 and 10 minutes, respectively. This suggests that the complete helium evolution occurring within the timeline of the propellant transfer.

## REFERENCES

1. I. D. Smith, "The Determination of the Helium Saturation Level of Monomethylhydrazine and MON-3 Nitrogen Tetroxide", Lyndon B. Johnson Space Center White Sands Test Facility, Document No. TR-244-001, 1979.
2. Reynolds, W. C., and Satterlee, H. M., "Liquid Propellant Behavior at Low and Zero g" in The Dynamic Behavior of Liquids in Moving Containers with Applications to Space Vehicle Technology, Ed. H. N. Abramson, NASA Report SP-106, NASA, Scientific and Technical Information Division, Washington, DC, 1966.
3. Marsh, W. R., and Knox, B. P., "USAF Propellant Handbooks: Hydrazine Fuels," Vol. 1, Defense Technical Information Center, Cameron Station, Alexandria, VA, 1970.
4. K. Coolidge, "Helium Solubility Rates in NTO and MMH", Report No. 287-201-81-086, Rockwell International, 1981.

Table 1. Steady-state Timeline of Helium Absorption and Evolution

Propellant	Amount (gram)	Beginning Pressure (psig)	De-saturation Pressure (psig)	Absorption Time (days)	Evolution Time (min)
NTO	95.0	200	0	22	~ 10
MMH	59.5	200	0	24	< 1

Figure 1. Process of Helium Evolution in the Transfer Line

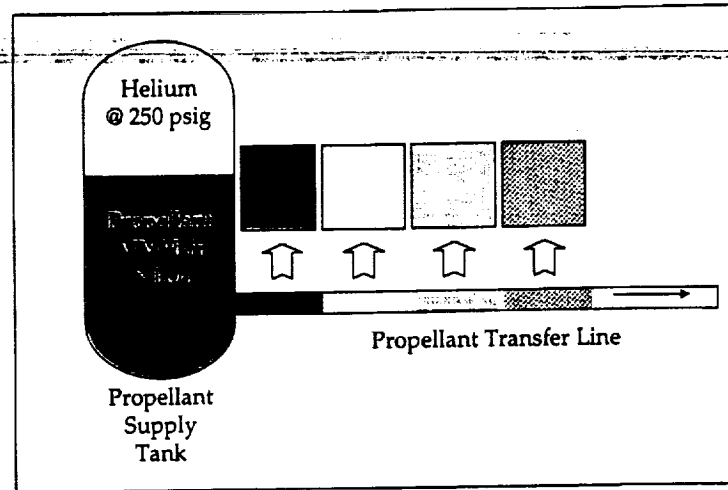


Figure 2. Orbiter Docking with the ISS

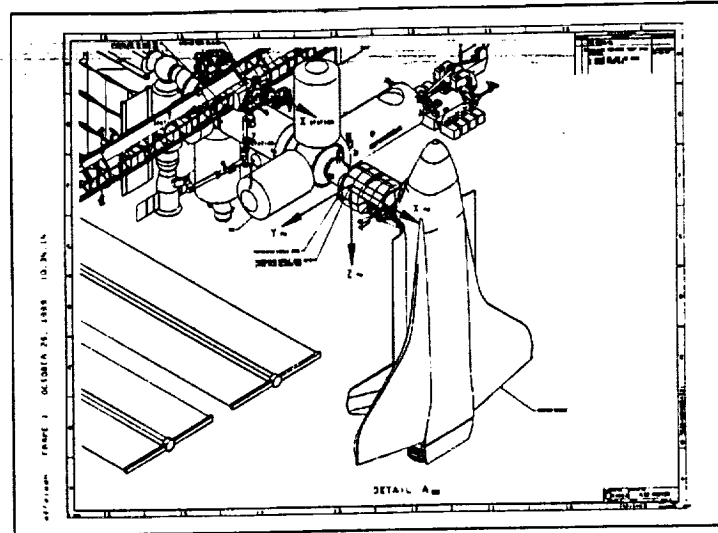


Figure 3. FICS and OPTS Fluid Transfer Line

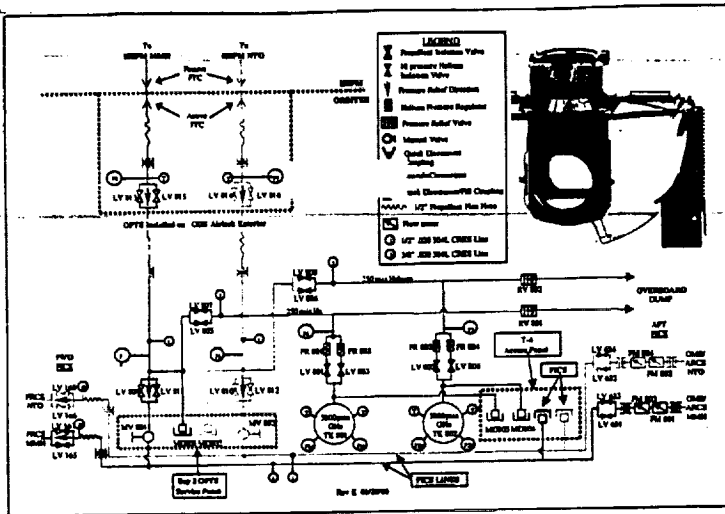




Figure 4. Pressure Profile along the Transfer Line

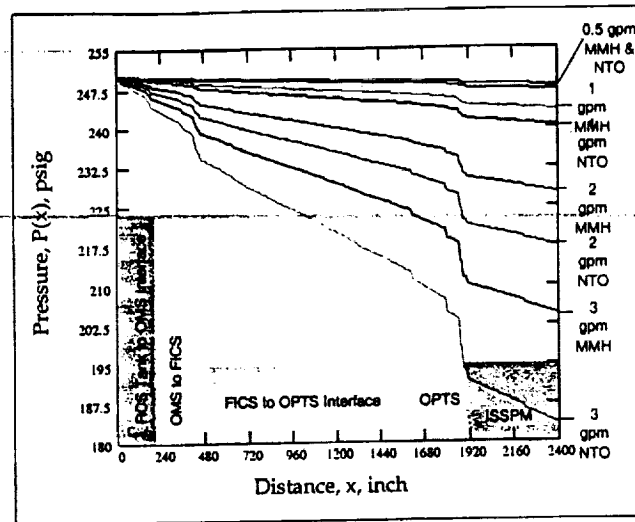


Figure 5. An Element of Propellant

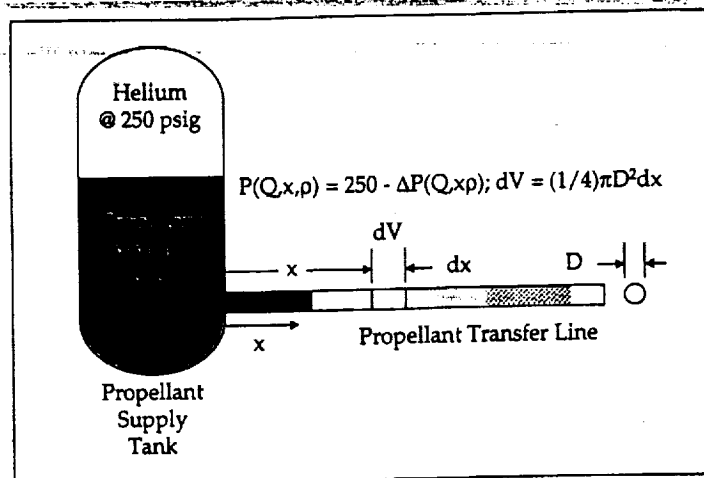


Figure 6. Amount of Helium Evolves from MMH during Propellant Transfer for Various Flow Rates (0.5 to 3.0 gpm)

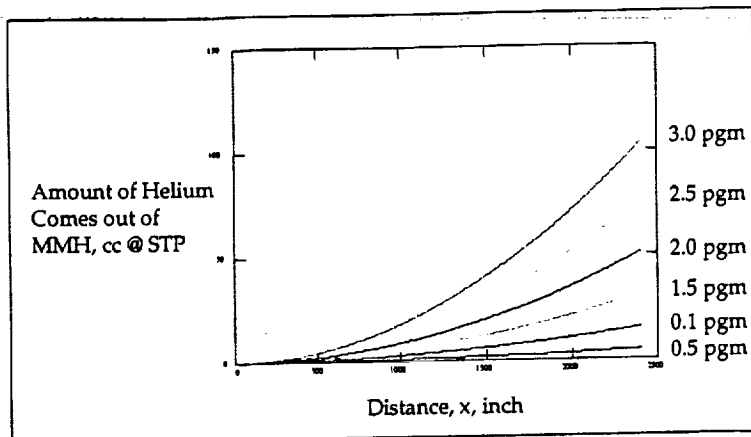


Figure 7. Amount of Helium Evolves from NTO during Propellant Transfer for Various Flow Rates (0.5 to 3.0 gpm)

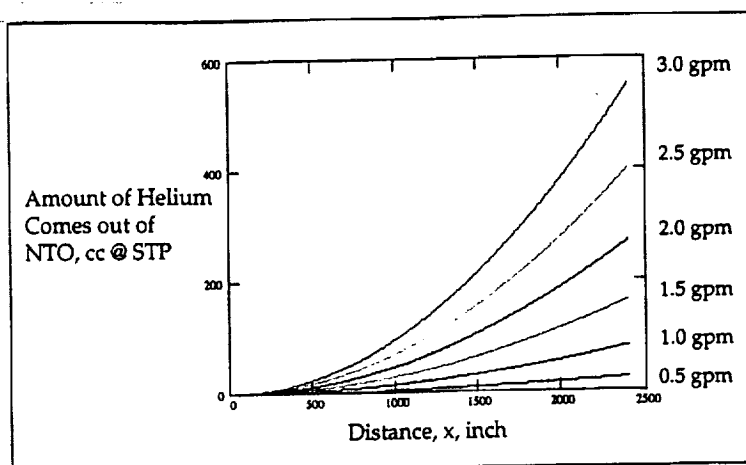


Figure 8. Volume Fraction of Helium to MMH during Propellant Transfer for Various Flow Rates (0.5 to 3.0 gpm)

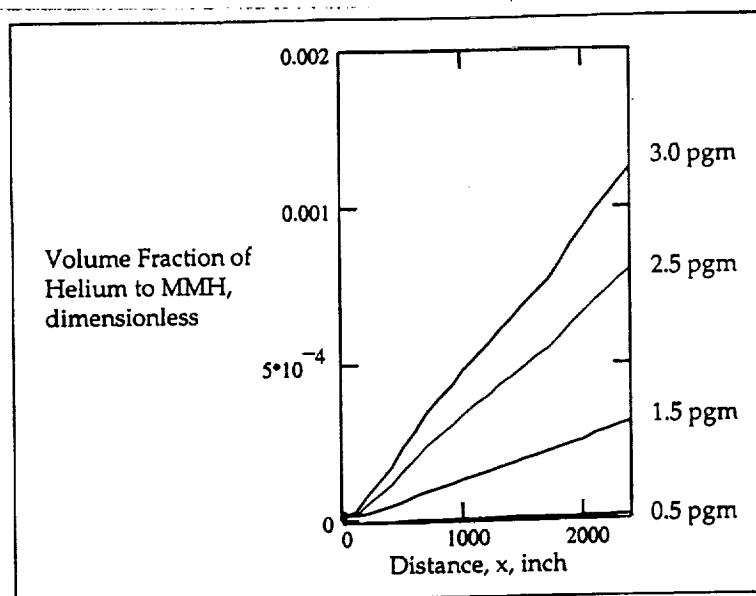


Figure 9. Volume Fraction of Helium to NTO during Propellant Transfer for Various Flow Rates (0.5 to 3.0 gpm)

